Fly-By-Wire for Experimental Aircraft?

A Vision based on CANaerospace/AGATE Data Bus Technology

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Introduction

While glass cockpit technology has found its way into light aircraft already, data buses and all-electric flight controls have not. Todays technology provides well-designed network standards which fulfill the data integrity and performance requirements of flight safety critical systems at reasonable effort. Implementing a low-cost avionics networks as a backbone enables the creation of state-of-the-art Integrated Modular Avionics (IMA) based systems for experimental aircraft. This paper describes such an IMA network, its present use and future applications to enable affordable, fly-by-wire technology for experimental aircraft.

The Integrated Modular Avionics Concept

Real-time airborne computer and network systems, consisting of a number of computing modules and capable of supporting various functions are referred to as Integrated Modular Avionics (IMA). The IMA concept was introduced by some of the main avionics suppliers in the 1990s and initially applied to fighters and business/ regional jets. In the meantime, even commercial airliners like the Airbus A380 and Boeing 787 now rely heavily on IMA. The IMA concept is the trend of the future for avionics due to the economies in fuel savings derived from less weight and lower cost.

IMA systems offer a significant weight reduction, lower development cost and offer substantial procurement and maintenance savings compared to traditional avionics system architectures. This is mainly achieved by the use of an avionics network backbone serving as a shared resource between IMA modules. This IMA network significantly reduces wiring (Figure 1), allows standardization of the network interface and relieves the application developers from spending excessive amounts of time on developing interfaces to other modules leaving more resources for the development of the application itself. IMA systems provide a unified network hardware/software interface which is used for all Line Replaceable Units (LRU) regardless of their specific task and level of functional centralization or decentralization. Taking advantage of standardized hardware/software components, upgrades and changes are both easier and less expensive to accomplish while communication-level software failures are greatly reduced. Development and maintenance of IMA modules is therefore easier than previous specific architectures, resulting in direct cost savings.

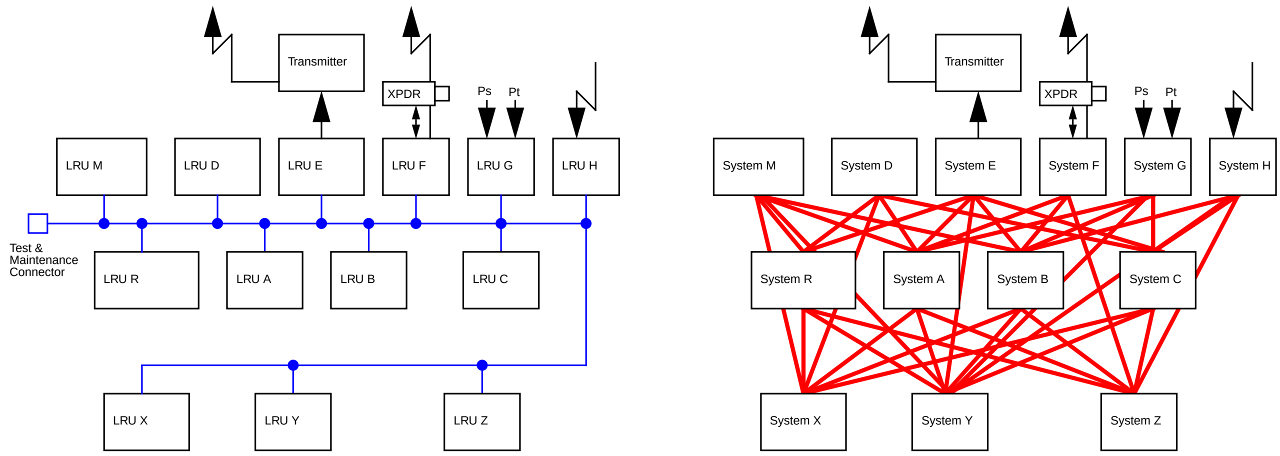


Figure 1: IMA Network compared to traditional Avionics System Wiring

By its nature, an IMA network also supports functional centralization and decentralization. Several functions can be combined in one LRU, sharing the internal hardware resources and reducing the overall unit count. Alternatively, a single complex function may be spread between several LRUs communicating with each other. With new aircraft having more software-based functions, and computers becoming more powerful, adding new features or functions during the aircraft life cycle can be accomplished more easily with IMA. The flexibility of IMA-based avionics also permit functions to be reconfigured on other modules if the module that supported them is detected as being faulty during operation, increasing the overall availability of the on board avionics. To support fault detection and isolation, a dedicated network communication layer allows the control of built-in test functions and collection of the corresponding results for continuous integrity monitoring.

Another important aspect to be considered for avionics systems is interoperability. In general, interoperability means the capability of two or more systems to communicate, exchange information and automatically interpret the exchanged information meaningfully and accurately in order to produce useful results as specified for the affected systems. The effort to ensure interoperability increases (a) linear and in some cases exponentially with the number of interfaces needed to provide the necessary exchange of information. For traditional avionics system architectures, interoperability has always been a challenge and often difficult to achieve. In IMA systems, the number of interfaces are substantially reduced; For some LRUs, it might even be limited to the IMA network. Interoperability for IMA modules is ensured by means of a network hardware interface specification and a common information exchange reference model which covers topics like standardized data formats and sign conventions.

Controller Area Network (CAN)

A candidate for an IMA network that combines adequate functionality and low cost is Controller Area Network (CAN). The CAN standard was developed by Bosch as an automotive data bus in 1983 and is the leading automotive communication network [1]. CAN offers significant advantages for reliable data communication in mission and safety critical applications making it attractive for aviation. CAN network components are both well-tested and inexpensive due to incredibly high production volumes.

CAN is a two-wire, multi-master broadcast serial bus standard that efficiently supports real-time control in distributed embedded systems. The CAN topology is a single cable with the LRUs connected in series or using small stub lengths with 120Ω termination resistors on each end of the network for bus termination as shown in Figure 2. Various bus interconnect methods like daisy-chaining or bundle splice are possible if properly done. A well-defined physical layer (ISO 11898-2) allows communication at data rates between 83kbit/s and 1Mbit/s. ISO 11898-2 specifies the CAN data bit representation, synchronization and electrical signal levels. Also defined are the electrical characteristics of bus transceivers and the transmission medium (twisted pair cable). CAN may be used with shielded or unshielded cables and with a variety of connectors, including affordable Sub-D types. For LRUs with low power consumption, the electrical power may be routed together with the CAN bus combining two twisted pairs into a single cable.

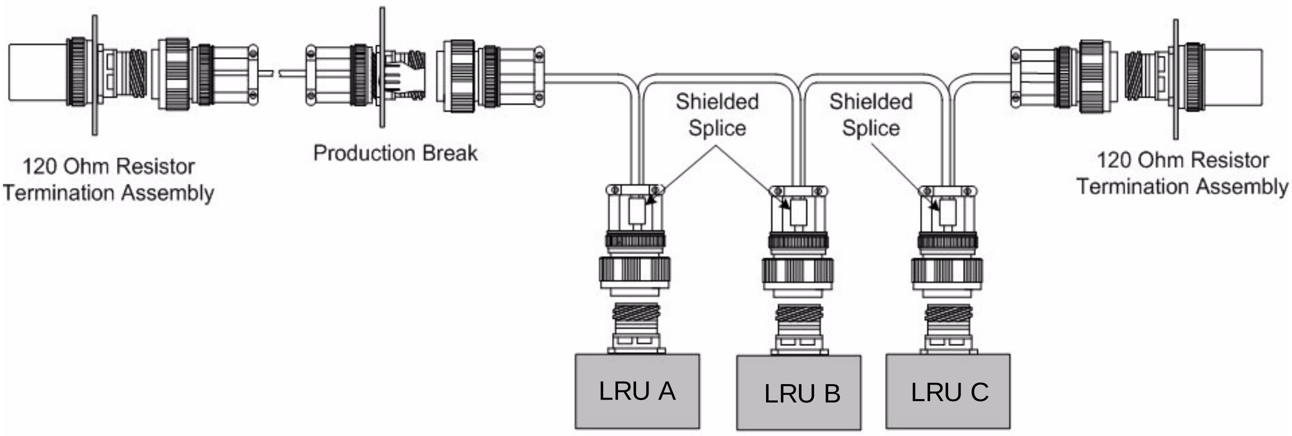


Figure 2: Typical CAN Network Installation in Aircraft

With respect to the electrical properties of CAN, the data rate is a function of the network length as shown in Figure 3. For light aircraft, the maximum data rate of 1Mbit/s can be used in most cases. The +/- 2.5V differential transmission ensures a high common mode rejection and a high level of electromagnetic immunity (EMI).

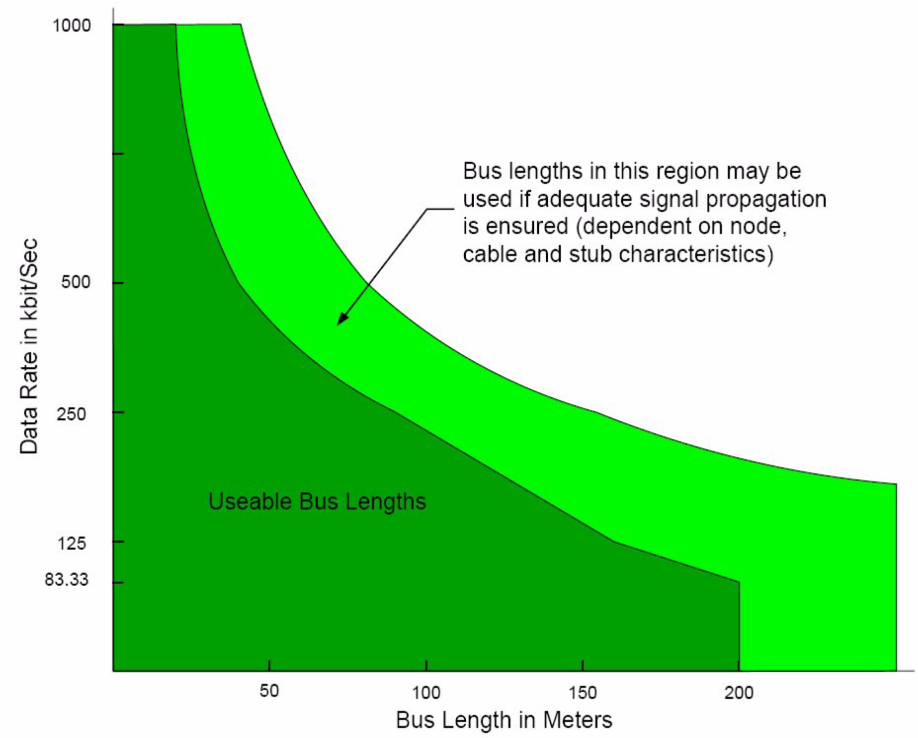


Figure 3: Relationship between CAN Data Rate and Bus Length

The number of nodes that may be attached to a CAN network segment depends on the minimum load resistance a CAN bus transceiver is able to drive. This load resistance is defined by the termination resistance, the bus line resistance and the differential input resistance of the bus transceivers. Therefore, the electrical characteristics of the cable and the integrity of the bus installation are important. Additionally, the long life cycle and specific operating environment of avionics systems has to be considered. To ensure adequate performance margin over the design life cycle, a certain amount of "capability de-rating" is usually applied. Table 1 represents successful systems experience based on the typical aircraft operating environment. The numbers given assume that all network components meet the criteria as set forth in ISO 11898-2.

CAN Data Rate (kbit/s)	Number of CAN Nodes (Typical Maximum)
1000	30
500	35
250	40
125	50
83.333	60

Table 1: Typical Relationship between Maximum Number of CAN Nodes and Data Rate

A significant advantage for CAN in comparison with other network standards is the fact that Logical Link Control (LLC) and Medium Access Control (MAC), specified in ISO 11898-1 and described in the layers 1 and 2 of the ISO open systems interconnection reference model (Figure 4) are contained in the network controller and transceiver chips. They do not require additional hardware or software. This fact eliminates any implementation-specific errors and deficiencies which are the potential result of numerous hardware/software developers colored interpration of the same network interface and protocol. Consequently, the hard coded CAN protocol has demonstrated excellent reliability in several hundred million CAN interfaces installed to date.

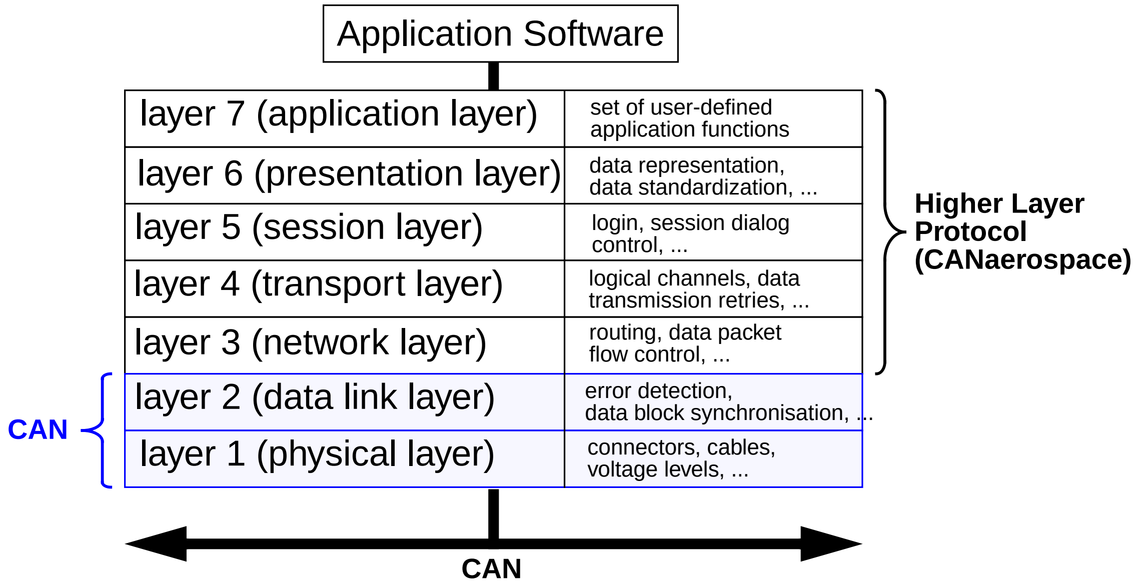


Figure 4: CAN and the ISO Open Systems Interconnection Reference Model

CAN is a broadcast bus using an object-oriented approach for data transmission. Any node on the network can start the transmission of a data frame if the bus is idle. CAN data frames (see Figure 5) have a payload size between zero and eight bytes and are preceded by a CAN Identifier. This CAN identifier serves a dual purpose:

First, it determines the priority of the data frame transmitted by the identifier, where the identifier with the lowest numerical value receives the highest priority. The priority has a direct impact on the order of transmitted messages, in cases where several modules are attempting to transmit on the bus at the same time. Second, the CAN identifier uniquely identifies the data frame so the data payload can be processed correctly in the receiving nodes. CAN supports two versions of identifiers with different lengths (11 bit and 29 bit), referred to as “standard” and “extended” identifiers. Both types may coexist on the same bus and do not interfere with each other.

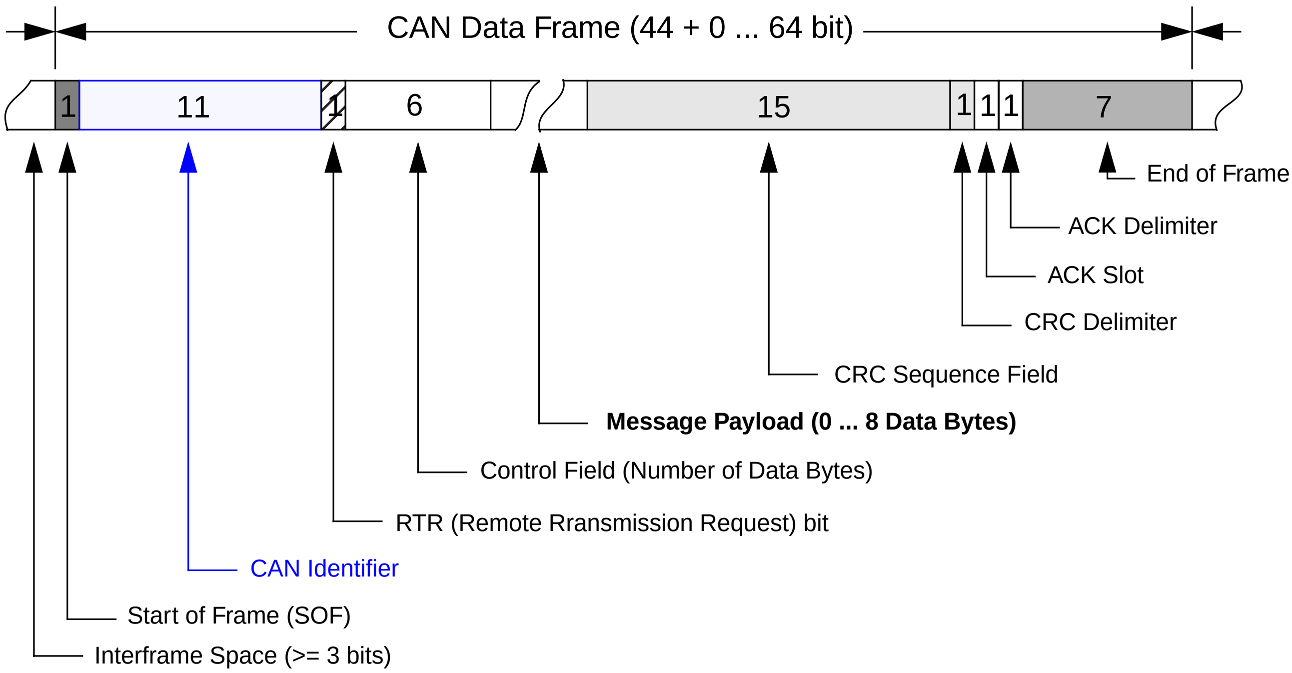


Figure 5: CAN Data Frame Structure (Standard CAN Identifier)

CAN is a multi-master bus and therefore has to resolve bus contentions caused when multiple nodes attempt to transmit messages at the same time. For this purpose, CAN uses a non-destructive arbitration method referred to as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The advantage of the non-destructive bitwise bus arbitration (Figure 6) is that no bandwidth is lost due to the arbitration process. Every node on the network continuously monitors the bus traffic (“line listen”) and acts accordingly. If a node loses arbitration, it will automatically participate in the next arbitration phase until it has successfully transmitted the pending data frame.

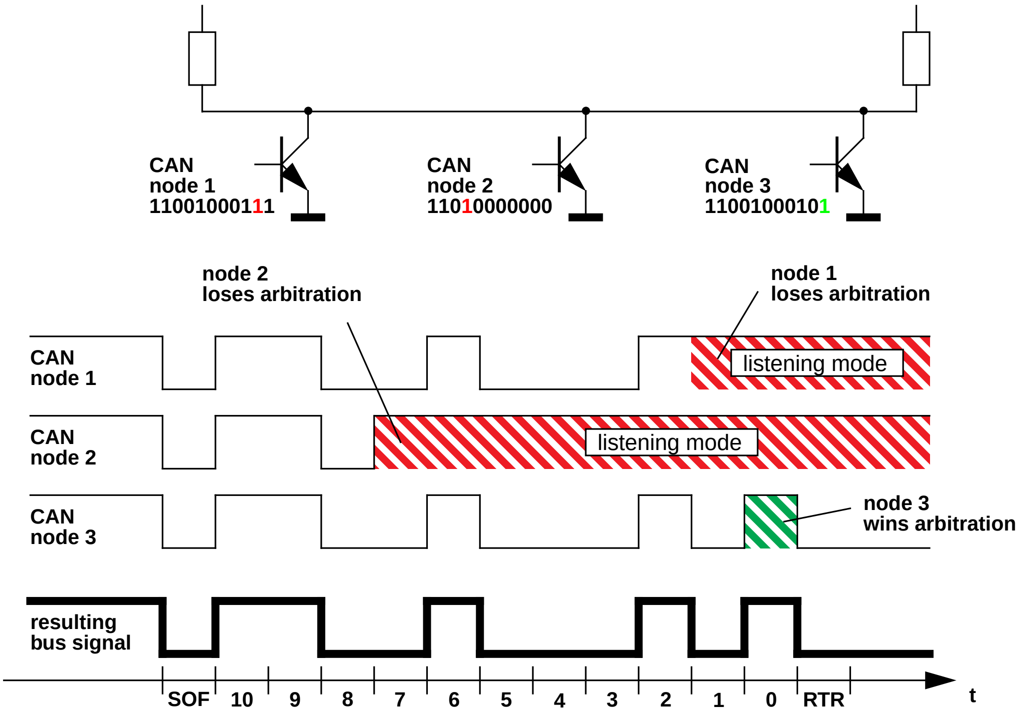


Figure 6: CAN-Identifier based Bus Arbitration (CSMA/CA)

CAN uses a highly sophisticated error detection and handling protocol, consisting of a 15-bit Cyclic Redundancy Check (CRC), frame structure, data acknowledge checking and bus signal monitoring. Any node on the network which detects an error during data transmission or reception immediately sends an error flag. This error flag destroys the current (faulty) message and causes the transmitting station to abort the transmission. All nodes then disregard the current message and check to see if they were the cause of the error. A node that identifies itself as the cause of the error increments an internal error counter; A node who’s internal error counter has exceeded the limit withdraws from the bus and does not participate in further bus activities until re-attached by software. These measures minimize the risk of a single node taking down the entire bus. The CAN error detection and handling mechanisms provide an extremely low probability of undetected CAN bus data corruption (~ $4{,}7 \cdot 10^{-11}$ per message transmission according to Bosch literature).

The CANaerospace Standard

With an increasing number of CAN networks in avionics, a standard interface was required to allow interoperability and reusability of software modules and systems. This requirement was met by the CANaerospace standard [2], established in 1997. CANaerospace use has accelerated in the last twelve years mainly due to its unique protocol specification and as a solution addressing issues related to safety critical electronics. It covers not only the protocol itself but also deals with timing requirements, bandwidth management and hardware issues like connectors and cables.

CANaerospace is a lightweight interface definition requiring very little software for its implementation. Simplicity was one of the main design goals. Flight safety or mission critical systems are required to demonstrate function predictably under all conditions. Networks with bulky protocol stacks and high overhead cause implementation costs to increase exponentially while giving little or no advantage to general aviation aircraft. CANaerospace bridges the basic CAN protocol to a data communication system comparable to well-known avionics data buses like MIL-STD-1553B while offering exponentially lower cost. Being an open, royalty-free standard it continuously receives input from various organizations and individuals and was standardized by NASA as the “AGATE Data Bus” [3] in 2001 and (with some modifications for large transport aircraft) as ARINC 825 in 2007. CANaerospace has the following features:

- **Democratic Network:** No master/slave relationship is required for normal operation. Every node on the bus has the same rights for participation in the bus traffic.
- **Self-Identifying Message Format:** Information about the type of the data and the transmitting node is included in each message.
- **Message Numbering:** Continuous numbering of transmitted messages supports coherent data processing in redundant systems.
- **Message Status Code:** Information about the integrity of the data source is transported with each message.
- **Emergency Event Signaling Mechanism:** Information about failures detected by built-in-test functions is transmitted by the affected node.
- **Node Service Mechanism:** Addressing of specific nodes for integrity monitoring, data download, time synchronization or interrogation using connection-oriented and connectionless services is supported.
- **Identifier Assignment:** CANaerospace offers a predefined identifier distribution for normal operation data (similar to Mark 33 DITS for ARINC429). More than one identifier distribution scheme is supported.
- **Ease of Implementation:** The amount of code to integrate CANaerospace into safety or mission critical software is very small to minimize the effort for testing and certification.
- **Openness to Extensions:** All definitions are extendable to provide flexibility for future enhancements and requirements of specific applications. Standard and Extended CAN identifiers (11/29 bit) are supported at the same time.
- **Free Availability:** Absolutely no cost or royalties apply for use of CANaerospace or its specification.

CAN is a multi-drop network using broadcast (also referred to as anyone-to-many) communication. The advantage of anyone-to-many (ATM) communication is that it creates inherent data consistency between all nodes in the network as they all participate to the network health. Both periodic and aperiodic data transmission during normal operation is possible. The shortcoming of CAN is that there is no inherent peer-to-peer (PTP) communication mechanism meaning that CAN nodes cannot be addressed individually without further protocol enhancements. CANaerospace provides these enhancements.

ATM communication avoids overhead and makes effective use of available bandwidth. Nevertheless, to relieve receiving nodes from the task of processing data that they do not need, hardware acceptance filtering within the CAN controller may be used to block incoming messages not referenced by the affected node from being passed upward into layers implemented in software, thereby saving precious CPU time.

PTP communication allows client/server type interactions between all nodes in the network and is necessary to request certain actions from a specific node. The idea behind this concept is that any node in the network may be a client for one task and a server for another task at the same time. By this concept, functions may be distributed over the network, unleashing the real power of distributed systems. PTP communication distinguishes between connectionless (no response transmitted) and connection-oriented (handshake type) communication, similar to UDP/IP and TCP/IP with Ethernet.

Using both ATM and PTP communications at the same time requires multiple network layers supporting different functions while isolating them from each other. In order to provide these multiple network layers with associated message types, CANaerospace groups the CAN identifiers as shown in Table 2. This structure implements Logical Communication Channels (LCC), ATM and PTP communications in an effective way to minimize the software implementing the CANaerospace standard. This is beneficial as many CAN nodes will be low-power cost-driven implementations, ruling out bulky communication layers with lots of overhead. By utilizing user-defined LCCs, the system designer is given a high level of freedom to make use of the network according to the designer’s needs.

The CAN identifier bit range assigned to LCCs has an impact on message prioritization and bus arbitration. Consequently, the communication channels are prioritized according to their importance.

Logical Communication Channel Acronym	Logical Communication Channel Message Type	CAN Identifier Range	Description and Communication Type (ATM/PTP)
EED Highest Priority	Emergency Event Data	0 - 127 (128 Identifiers)	ATM messages transmitted asynchronously whenever a situation requiring immediate action occurs
NSH	Node Service Data (High Priority)	128 - 199 (72 Identifiers)	PTP messages transmitted asynchronously or cyclic with defined transmission intervals for operational commands (36 PTP channels)
UDH	User-Defined Data (High Priority)	200 - 299 (100 Identifiers)	ATM messages with user-defined message/data format and transmission intervals
NOD	Normal Operation Data	300 - 1799 (1500 Identifiers)	ATM messages transmitted asynchronously or cyclic with defined transmission intervals for operational and status data
UDL	User-Defined Data (Low Priority)	1800 - 1899 (100 Identifiers)	ATM messages with user-defined message/data format and transmission intervals
DSD	Debug Service Data	1900 - 1999 (100 Identifiers)	User-defined messages, transmitted asynchronously or cyclic for node specific debug communication actions
NSL Lowest Priority	Node Service Data (Low Priority)	2000 - 2031 (32 Identifiers)	PTP messages transmitted asynchronously or cyclic for test & maintenance actions (16 PTP channels)

Table 2: CANaerospace Logical Communication Channels and Message Types

As the majority of the embedded systems use processors with Big Endian CPU architectures, CANaerospace uses Big Endian representation exclusively. According to the Big Endian definition, the most significant bit (MSB) of any datum is arranged leftmost and transmitted first as shown in Figure 7.

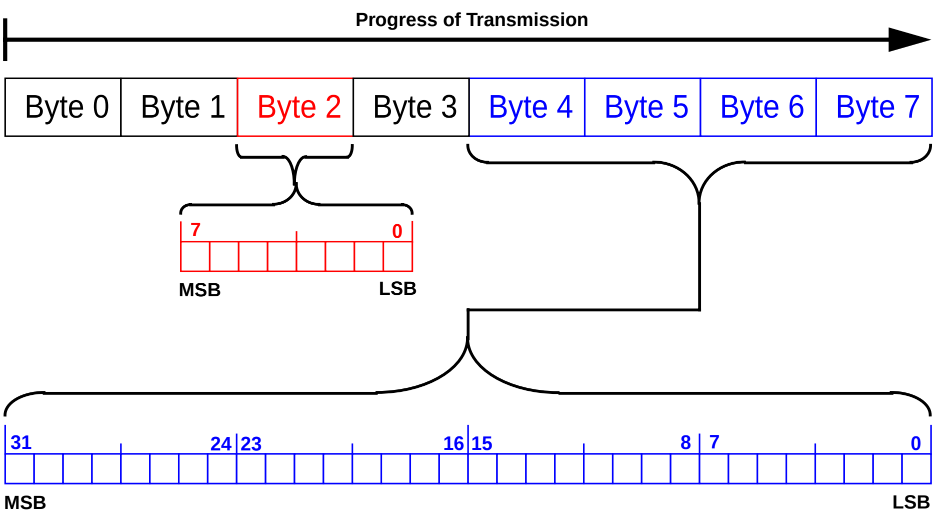


Figure 7: Big-Endian Data Representation used by CANaerospace

CANaerospace uses a self identifying message format which is realized by structuring the CAN message payload as shown in Figure 8. This structure creates a 4-byte message header and a 4-byte message data section. Every CANaerospace message type (see Table 2) uses the same layout for the message header (Byte 0-3), while the message data section (Byte 4-7) has a variable length of 0 to 4 bytes and a message specific structure.

The CANaerospace message header allows all nodes in the network to identify each message including its specific properties without the need for additional information. With this header, listening to a CANaerospace network and interpreting the data on the bus correctly is simplified. The self-identifying CANaerospace message format maximizes interoperability and supports efficient system monitoring at the same time. Table 3 explains the meaning and use of the CANaerospace message header bytes.

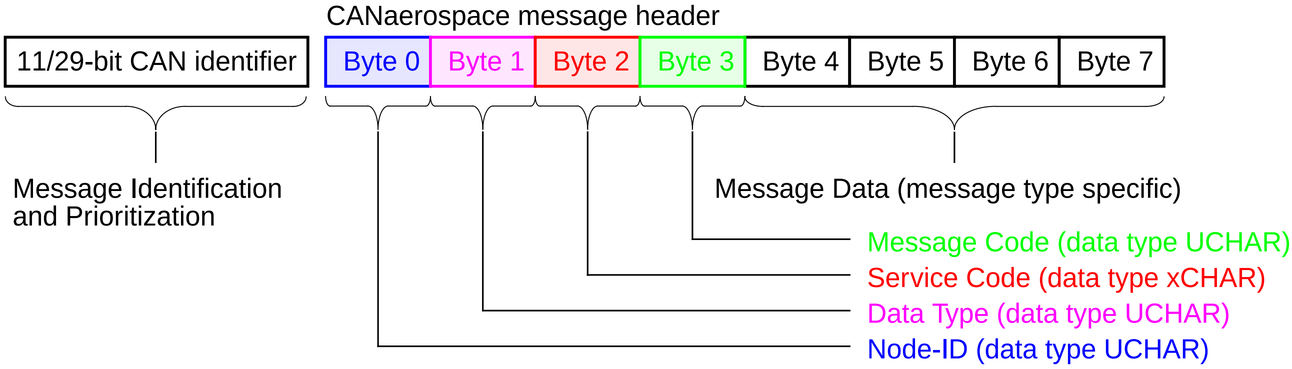


Figure 8: CANaerospace Message Format

CANaerospace Message Header Byte	Description
Node-ID	The Node-ID is in the range of 0-255 with Node-ID “0” being the broadcast-ID referring to “all nodes”. For emergency event data (EED) and normal operation data (NOD) messages, the Node-ID identifies the transmitting station, while for node service data (NSH/NSL) messages the Node-ID identifies the addressed station. Some systems reconfigure themselves in case a unit fails. The Node-ID allows immediately identifying this situation and reacting accordingly (i.e. mode change or backup function activation).
Data Type	The data type specifies how the data transported with the corresponding message shall be interpreted. The Data Type code is taken from the CANaerospace data type list. CANaerospace supports multiple data types for every message. Backup units (or units from different vendors) may use different data types while performing identical functions. Specifying the data type with each message allows automatic system configuration.
Service Code	For normal operation data (NOD) messages, the service code consists of 8 bits which may be used as required by the specific data (should be set to zero if unused). For node service data (NSL/NSH) messages, the service code contains the node service code for the current operation. For Normal Operation Data, this byte should continuously reflect the status of the data (or the transmitting unit) to support data integrity monitoring within receiving units. With this information, the validity of data is known at any given time.

CANaerospace Message Header Byte	Description
Message Code	For normal operation data (NOD) messages, the message code is incremented by one for each message and may be used to monitor the sequence of incoming messages. The message code rolls over to zero after passing 255. This feature allows any node in the network to detect missing/delayed messages and determine the proper sequence. For node service data (NSL/NSH) messages, the message code is used for extended specification of the service. Message numbering detecting whether messages are missing and if the transmitting unit is operating properly. Also, it can be used to compare the "age" of messages from redundant sources.

Table 3: CANaerospace Message Header Description

CANaerospace ensures interoperability through well-defined data formats and sign conventions known to all nodes in the network in order to interpret received data correctly and transmit properly calculated and formatted data. Consequently, the CANaerospace standard defines data types, sign conventions and engineering units. Additionally, a predefined identifier distribution list makes sure that all parameters transmitted over a CANaerospace network are tagged unambiguously. For this purpose, the available identifiers for normal operation data have been grouped for the various aircraft systems, thereby reserving the identifier range 300-1499. Table 4 shows an extract from this list.

To provide adequate flexibility the CANaerospace data type, unit and identifier distribution lists have user-defined sections which allow missing definitions for certain applications to be added in a compliant manner.

CAN Identifier	System Parameter Name	Data Type	Unit	Notes
317	Calibrated Airspeed	FLOAT SHORT2	m/s	
321	Heading Angle	FLOAT SHORT2	deg	+/-180^{o}
401	Roll Control Position	FLOAT SHORT2	%	Right: + Left: -
500	Engine #1 N1 ECS Channel A	FLOAT SHORT2	1/min	N1 for jet , RPM for Piston Engines
1008	Active Nav System Track Error Angle (TKE)	FLOAT SHORT2	deg	Service Code Field Contains Waypoint #
1070	Radio Height	FLOAT SHORT2	m	
1205	Lateral Center of Gravity	FLOAT SHORT2	% MAC	

Table 4: Example for the CANaerospace Identifier Distribution List

An essential characteristic of all systems critical to flight safety is that their behavior can be precisely defined, analyzed and tested to meet formal certification requirements. This characteristic is often misinterpreted as microsecond-level timing “determinism” but is in fact predictability. The degree of precision required for timing is specific to each application and has to be quantified by system analysis. The ultimate target to be reached, however, is that it can be demonstrated to certification authorities that a safety critical system based on CANaerospace behaves predictably under all circumstances. Nodes transmitting high priority messages at a high rate can potentially consume an excessive amount of bandwidth, block out other nodes too often and cause unpredictable transmission delays. Such a scenario would also generate substantial jitter in the data transmission and must be entirely avoided. A suitable bandwidth management concept on the system level is therefore necessary to ensure that the bus load is within certain limits and evenly balanced over time.

Using CANaerospace, the required predictability can be achieved. CANaerospace sets forth a concept of managing the available bandwidth for one-to-many and peer-to-peer communication called “time triggered bus scheduling”. This concept is based on a limitation on the number of CAN messages that any node in the network may transmit within a "minor time frame" so that no single message is delayed beyond a tolerable limit. The minor time frame is defined during the initial system design. The maximum number of messages transmitted within one minor time frame may differ from node to node and contain growth potential if granted by system design. The concept takes advantage of the fact that not all messages in a given system have to be transmitted at the rate defined by the minor time frame interval. Specifying multiples of the minor time frame transmission interval and associated "transmission slots" allow a substantially larger number of parameters to be transmitted predictably.

The corresponding relationship, based on a typical CANaerospace network with 1Mbit/s data rate and standard CAN identifiers is shown in Table 5. If all CANaerospace messages in the network use the maximum payload of 8 bytes (worst-case assumption), the length of each message is 44bits + 64bits = 108bits. To compute the maximum bus capacity, the inter frame space (3bits) and an average number of 14 stuff bits must be added, resulting in a total data frame length of 108bits + 3bits + 14bits = 125bits (see also Figure 5). At 1Mbit/s data rate, such a CANaerospace message takes 125µs to transmit. The CANaerospace bus capacity for this example is therefore 8.000 messages per second which means that either 100 parameters transmitted every 12.5ms or 8000 parameters transmitted once a second would generate 100% bus load. In reality, however, a combination of parameters in the various transmission slot groups from Table 5 will be used.

Transmission Slot Group	Transmission Interval	Maximum Number of Parameters per Transmission Slot	Number of Transmission Slots (equalling 100% bus load)
A	12.5ms (80Hz)	1	100
B	25ms (40Hz)	2	200
C	50ms (20Hz)	4	400
D	100ms (10Hz)	8	800
E	200ms (50Hz)	16	1600
F	400ms (2.5Hz)	32	3200
G	1000ms (1.0Hz)	80	8000

Table 5: Relationship between Multiples of the Minor Time Frame and available Transmission Slots

Every node in the network must adhere to its transmission schedule at all times when generating network traffic. However it is *neither* required *nor* prohibited that nodes in the network synchronize to other nodes concerning their message transmission order or transmission times. Applying the time triggered bus scheduling concept, it can be demonstrated that CANaerospace networks can behave predictably.

Error frames may lead to unpredictable behavior if the bandwidth is consumed by error frames resulting from faults of the network or the nodes attached to it. Therefore, it is recommended to limit the bandwidth usage to 50% of the maximum bandwidth limiting the potential for unpredictability. While the time triggered bus scheduling concept requires margins and does not optimize network bandwidth usage, it provides a safe and straightforward approach to build certifiable (predictable) systems. Figure 9 shows the transmission schedule example of a CANaerospace network with two nodes transmitting their messages asynchronously, in alternating order and at random times within their minor time frames (worst case scenario). This example utilizes 50% of the maximum bandwidth.

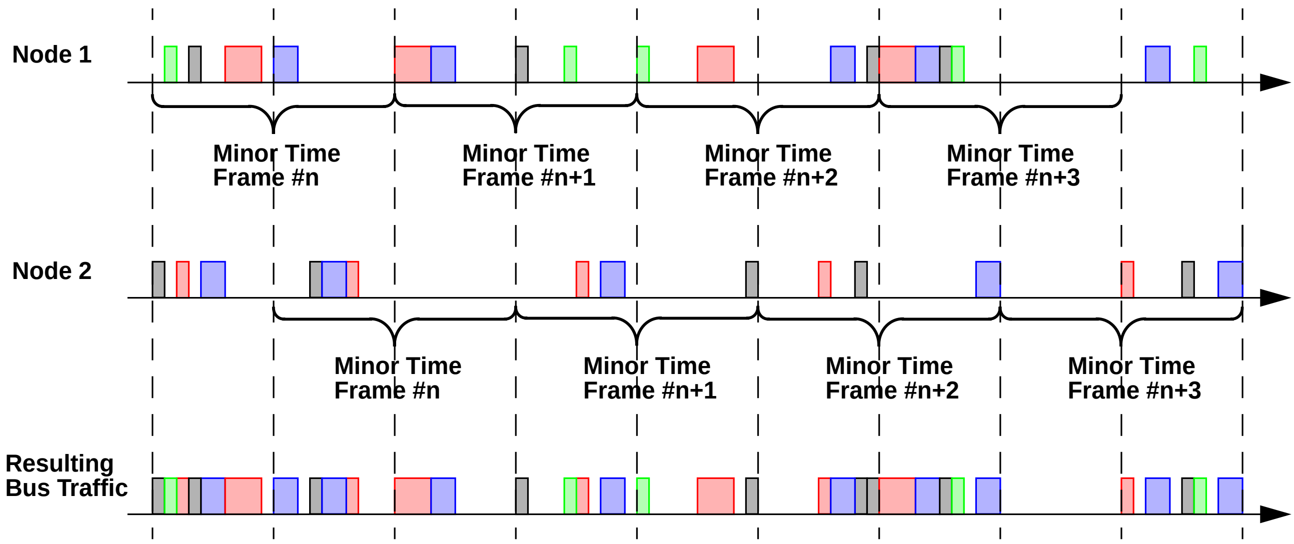
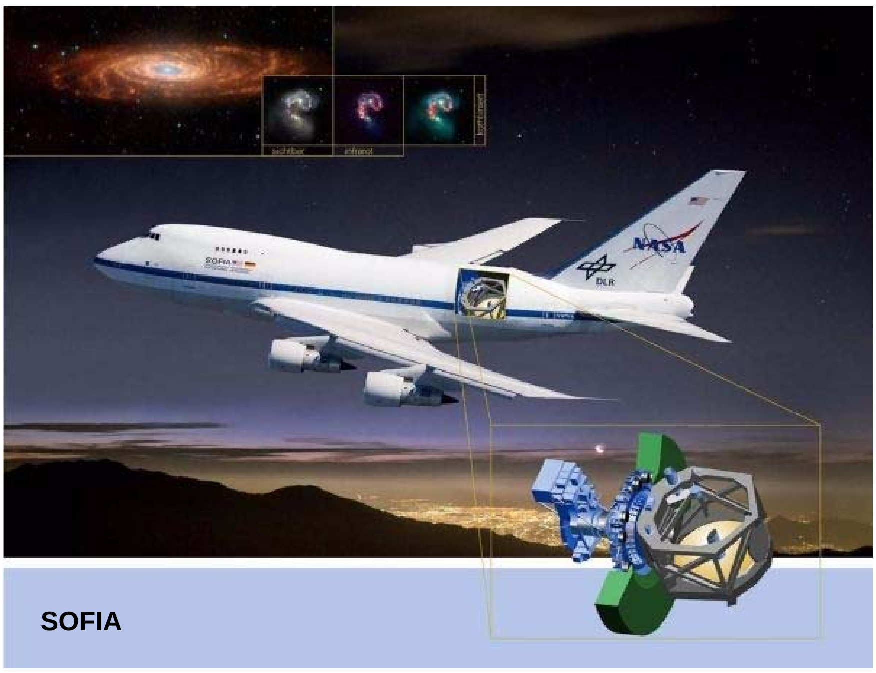


Figure 9: Predictable Bus Traffic at 50% Bus Load based on Time Triggered Bus Scheduling

CANaerospace Application Examples

Since 1998, CANaerospace has demonstrated its reliability and performance in many aircraft all over the world including the SOFIA Boeing 747SP, the SATS airplanes operated by the NASA Langley Research Center, several flight data recording systems, engine control units and the FAA certified avionics system of the Ae270 small transport aircraft. Some of these applications are briefly described below to give an impression of how CANaerospace is already used to provide reliable communication for IMA systems.

CANaerospace interconnects mission critical real time systems in the Stratospheric Observatory For Infrared Astronomy (SOFIA) Boeing 747SP which accommodates the largest airborne observatory in the world using an optical telescope with a reflecting surface of 2.5m at the primary mirror. The CANaerospace buses travel through the entire aircraft and provide the connection between various subsystems performing functions such as star tracking control positioning, pressure window control and temperature/pressure monitoring around the telescope assembly structure. CANaerospace also interconnects the SOFIA operator station annunciation panels.

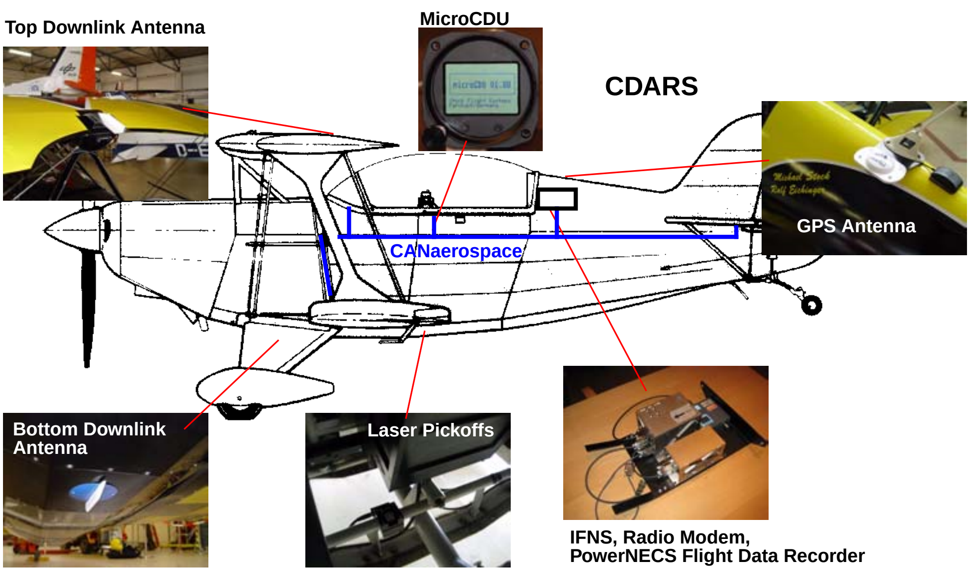


The NASA Langley Research Center has installed the CANaerospace/AGATE data bus in two research aircraft used for the SATS program flight tests. The CANaerospace bus is used as a backbone network for flight state sensors, navigation systems and several research PCs driving high resolution flat panel displays in the cockpit.

For research purposes, the two Langley aircraft are equipped with an airborne instrumentation system which records all relevant flight state data including the CANaerospace data stream. Together with a voice/video recording installation, the amount of data generated by the test flights allows an analysis of the crew support provided by advanced cockpit interfaces.

CANaerospace was reviewed by the FAA resulting in certification of the CANaerospace based SAM integrated avionics system on the Ae270 aircraft, designed by Unis s.r.o (www.unis.cz). SAM comprises of seven intelligent units which communicate to each other using CANaerospace. All SAM units are qualified according to RTCA DO-160D/DO-178B and meet HIRF (High Intensity Radiated Fields) requirements. The certification is based on FAR part 23. The SAM functions include electric power supply monitoring, fuel distribution and supply control, hydraulic system control, propeller heating control, airframe load monitoring and windshield deicing control.

The CANaerospace flight Data Acquisition and Recording System (CDARS) is an IMA-based flight test instrumentation system designed towards the specific requirements of light aircraft. CDARS provides a number of configurable sensor, data recording and telemetry units that communicate to each other using CAN aerospace. A miniaturized multifunction control and display unit (Micro CDU) allows data monitoring, system configuration and data recording control by the pilot or flight test engineer. CDARS inertial measurement unit delivers flight state, air data and GPS data even during advanced aerobatic maneuvers at a rate of 50Hz without interruption.



The RV-7ca Integrated Modular Avionics System

Today's complex avionics packages for experimental aircraft offer performance and features found in or even exceeding those found in many general aviation aircraft. As we install these systems, the complexity of wiring the airframe along with the ability to craft a seamless flight control system is getting increasingly difficult. EFIS 'compatibility issues' and the number of electrical connections needed to complete a complex avionics system has become a 'heavy' issue for builders.

The goal of the RV-7ca project is to reduce the installation complexity, improve sensor and actuator utilization, and reduce the electrical wiring. To accomplish these goals a new system based on IMA concepts and CAN-aerospace is being developed for experimental aircraft. The project is divided into three test phases. Phase two is covered in this presentation.

Phase 1

In phase one of this project, several isolated IMA modules are being tested in an existing RV-6A airframe. These IMA unit's control trim tabs, power distribution, flaps and include supporting systems such as non-contact angle sensors, and a 'serial stick grip' (SSG) interface. Several items have already completed their preliminary testing.

Phase 2

The second phase of this project involves the installation of these devices in a new RV-7 under construction. Five IMA units will be installed as a system. They will decentralize the power distribution, simplify the wiring harness, and manage both the trim and flap systems.

Phase 3

The CANaerospace system will be tested with third party devices allowing them to share the CAN bus for communications with their own proprietary sensors while maintaining their ability to monitor CANaerospace messages of interest from other CANaerospace compliant devices.

RV-7ca Phase 2 goals

For the trim and flap systems, the IMA configuration is projected to reduced electrical wiring by more than 80%* while creating a system capable of advanced features such as speed sensitive trim controls, trim presets based on flight phase, and safety alerts for events like flap deployment above V_f.

Electrical systems will also benefit with reduced size and complexity. Instead of point to point wiring between individual system loads such as landing lights, Pitot heater, etc. A power mains topography will distribute primary power to IMA units in the aircraft. The IMA units then distribute and control the electrical loads locally. The phase 2 module targets and locations are shown in Table 6 and Figure 10.

Location	Identifier	Target
1	Control Panel	Panel Switches and Lamps, Avionics/EFIS Bridge, Starter
2	Left Wing	Landing Light, Position Light, Pitot Heater, Roll Trim
3	Cabin	Strobe, Boost Pump, Cabin Lamp, Flaps, Stick Grip
4	Right Wing	Landing Light, Position Light
5	Empennage	Position Light, Aux Lighting, Pitch Trim, GPS Bridge

Table 6: Phase 2 Module Targets

*Traditionally trim and flap control systems needed five wires from each servo the length of the airframe back to the control panel. With this system, the control wires terminate locally at the trim module while their information is transferred over the 2-wire CAN bus.

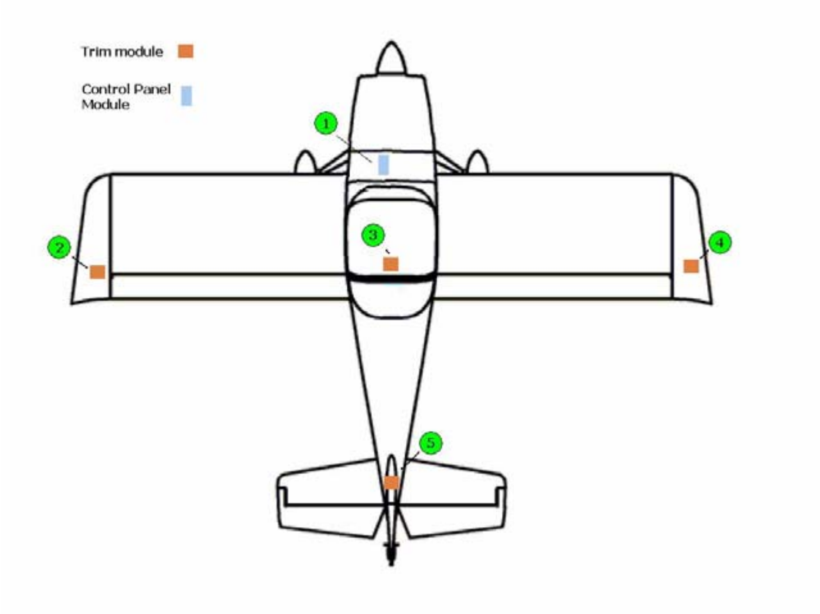


Figure 10: Phase 2 Module Locations

RV-7ca Electrical Harness

The CAN bus can be viewed as a single long twisted pair wire. Starting Fire Wall Forward (FWF) to monitor power plant activities, drop points are created by inserting IMA units directly in the cable path or by creating short cable stubs. Each end of the bus is terminated with a passive termination resistor as shown in Figure 11.

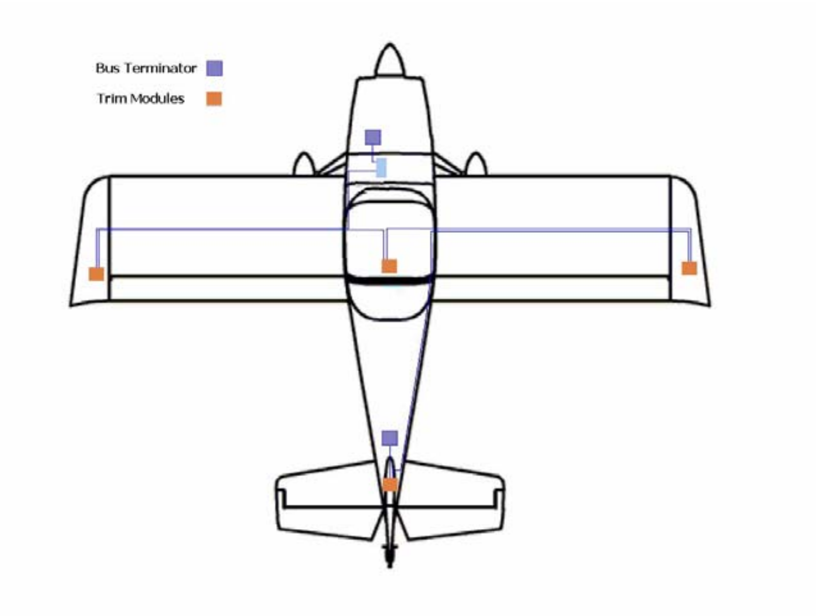


Figure 11: CANaerospace Bus Routing

From circuit breakers in the control panel, power is distributed to each IMA module. The individual modules control and monitor up to three electrical loads and one trim tab or flap servo. This topography reduces the number of electrical circuits routed from the control panel. It also allows symmetrical systems such as lighting an additional measure of redundancy* as each load is individually powered, controlled and monitored (see Figure 12).

* With each landing light on a different circuit and switch, we have reduced the possibility that a single point of failure will render both landing or all position lights inoperable.

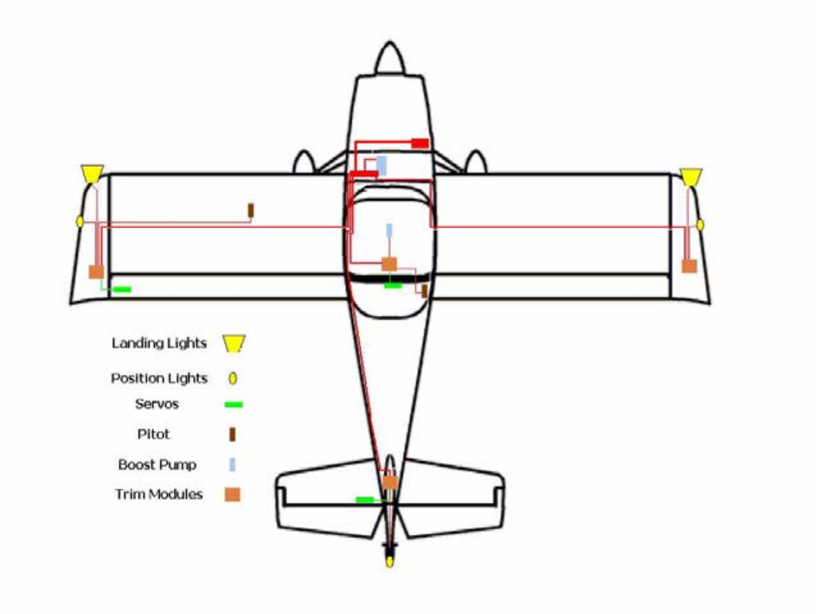


Figure 12: Primary Electrical Paths

The IMA Control Panel Module

The Control Panel module serves as a bridge between existing parallel wired legacy hardware and the CAN-aerospace network. The device can be updated with new software and configuration files supporting new functionality as software is written. The hardware on this card includes:

- Power drivers to control and monitor up to three 20amp loads
- Solid state altimeter (Blind Encoder)
- Two RS-232 ports
- Twelve lamp/LCD drivers
- Sixteen switch inputs
- Four dry contacts (Relays)
- Three RDAC drivers
- CAN bus interface
- Two Fuel level ADCs
- Lamp Dimmer input

Using the Control Panel module, existing commodity switches* and display devices can be leveraged by removing their original point to point wiring and using this module to transfer that information over the CAN bus. In this way aircraft with traditional steam gages can benefit from the reliability that a reduced wire count brings without upgrading to a full glass cockpit.

Two serial ports are uncommitted for future service as a bridge between existing EFIS systems and the sensors and actuators located on the CAN bus. Writing different software, two different EFIS systems can also share their data by converting their RS-232 data streams to a common interface (CANaerospace). The block diagram of the Control Panel Module is shown in Figure 13.

*Critical flight systems such as magnetos, while not controlled through CANaerospace, can also be mapped to CANaerospace identifiers allowing their switch positions be remotely confirmed.

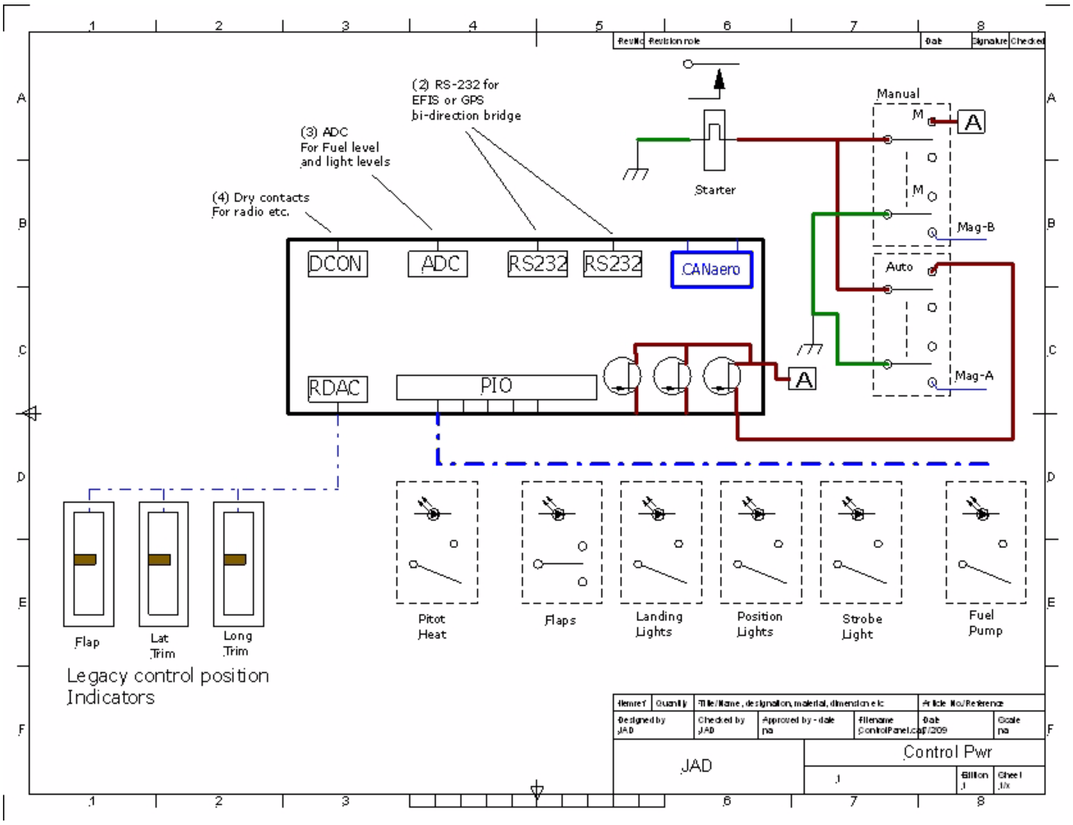


Figure 13: Block Diagram of the Control Panel Module

The IMA Trim Module

The CANaerospace Trim module is a multi-function IMA unit designed for light aircraft. Using technology from the automotive industry, this simple module leverages the high volume low cost components used in late model automobiles to create a robust, low cost device well suited for the control of basic servos and electrical loads.

This IMA module includes a choice of two different bridged motor drives, analog to digital converter, generic serial bus, RS-232 port, isolated CAN interface, and three solid state switches. Using a CAN bus integrated micro controller and intelligent power switches this module uses less than 10 active components.

- Bridge driver and ADC I/O for local trim and flap servos
- Power drivers to control and monitor up to three 20amp loads
- Internal voltage and temperature sensor to monitor environment and source power
- CAN bus interface
- GSB interface for I2C, SPI, or unbuffered sync/async data streams
- RS-232 interface

The block diagram of the trim module and its packaging are shown in Figures 14 and 15.

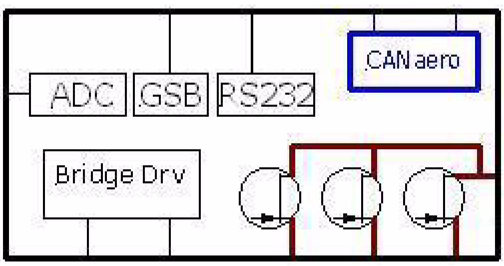


Figure 14: Trim Module Block Diagram

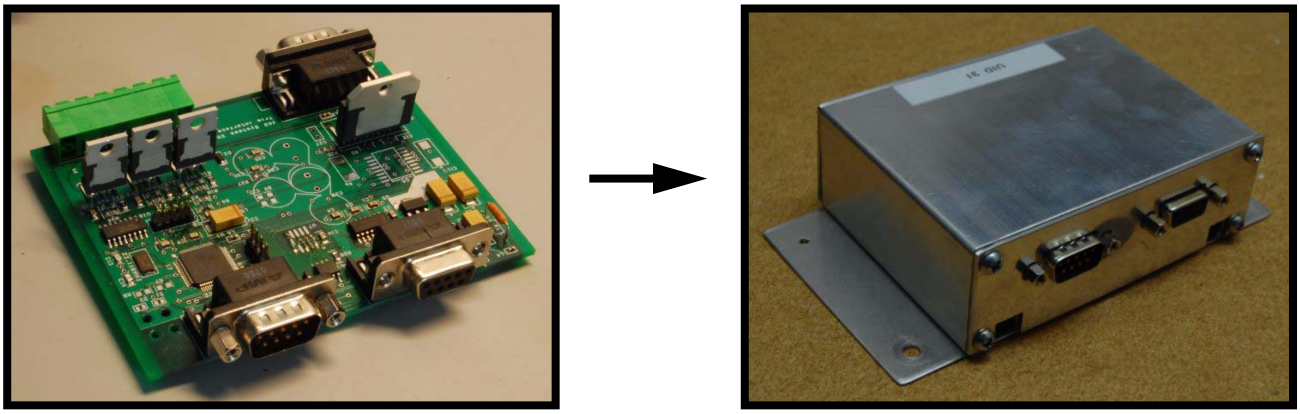


Figure 15: Trim Module Packaging

The IMA Serial Stick Grip Module

The Serial Stick Grip (SSG) as shown in Figure 16 uses Inter-IC bus (I2C) to eliminate large wire bundles. I2C is very similar to CAN. This serial protocol supports multiple devices and a non-destructive bus negotiation for priority based messages. While I2C does share many protocol similarities with CAN, the hardware interface is *not* suitable for use between devices on different power circuits or over long distances. This limits its usefulness to local I/O expansion.

The SSG protocol is based on CANaerospace to make bridging data between the two bus systems easier. The SSG connects to the nearest IMA unit's GSB port. The IMA's hardware and software supply power and creates a communications bridge to CANaerospace. By limiting the wire length and powering the device directly from the local IMA, the SSG is a very simple circuit requiring only two active components.

The SSG controller fits inside the pilots stick grip and connects to the IMA mounted in the cabin of the RV-7. By utilizing a SSG to augment CANaerospace, we eliminate the large parallel cable and relay board common to many stick grip installations as shown in Figure 17.

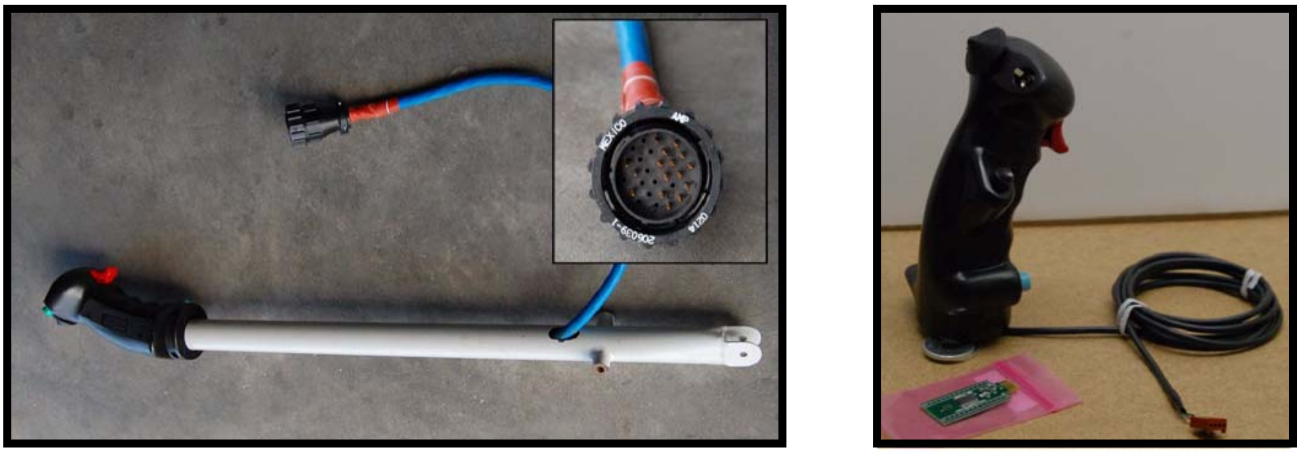


Figure 16: Traditional Serial Stick Grip (left) and Grip with SSG Controller

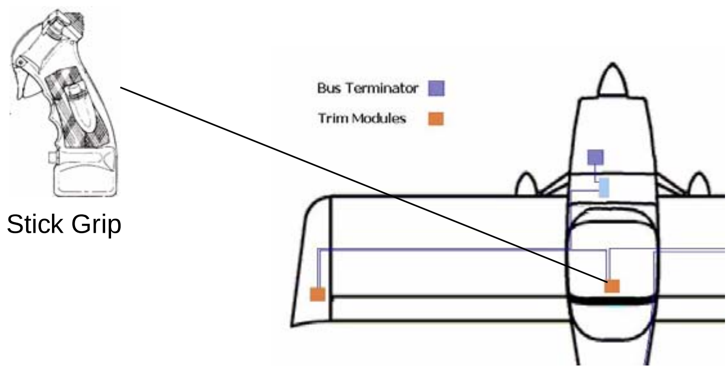


Figure 17: Stick Grip Connection

Non-Contact Angle Sensor

The RV-7ca flap system contains a new non-contact style angle sensor. This magnetic angle sensor has a 45 degree detection range and a proportional analog output similar to existing mechanical sensors. The sensor above is installed in the center section of the RV-7 cabin* and supplies position data to IMA module #3. A small button magnet bonded to the knuckle of the flap torque rod creates the reference magnetic field used to detect flap position (angle). The installation is shown in Figures 18 and 19.

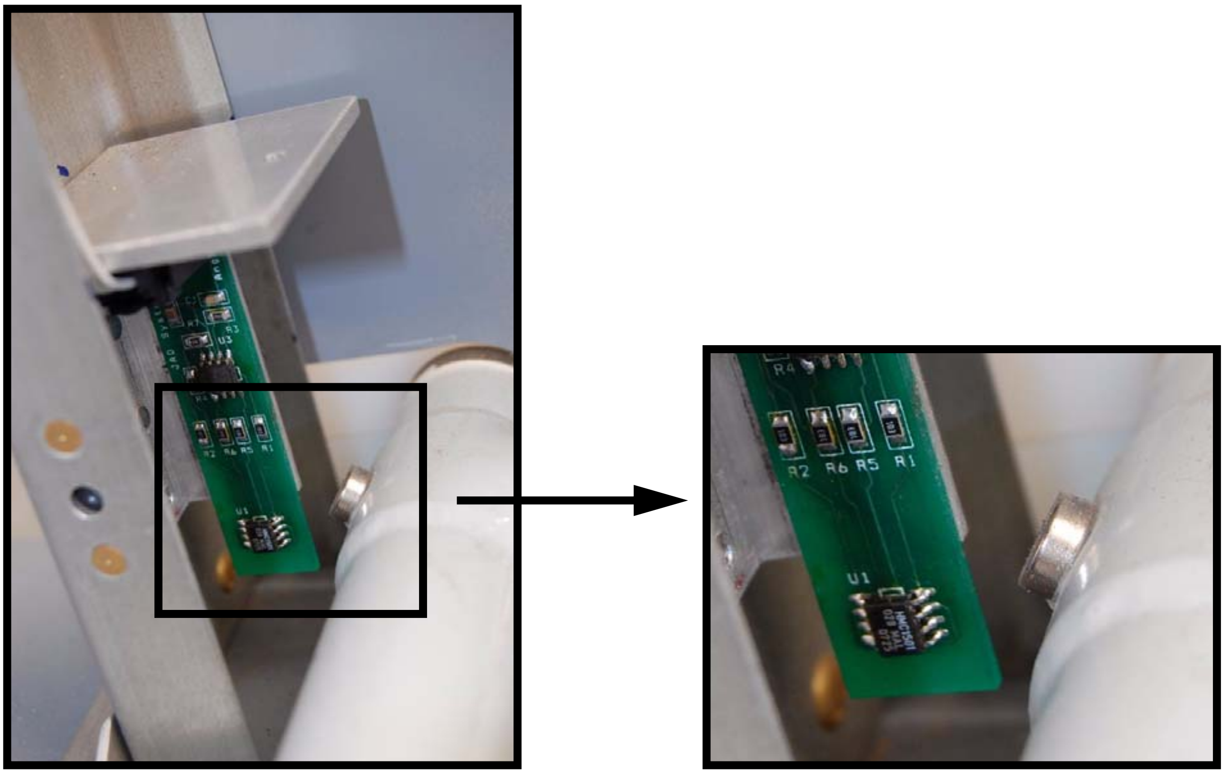


Figure 18: Non-Contact Flap Position Sensor

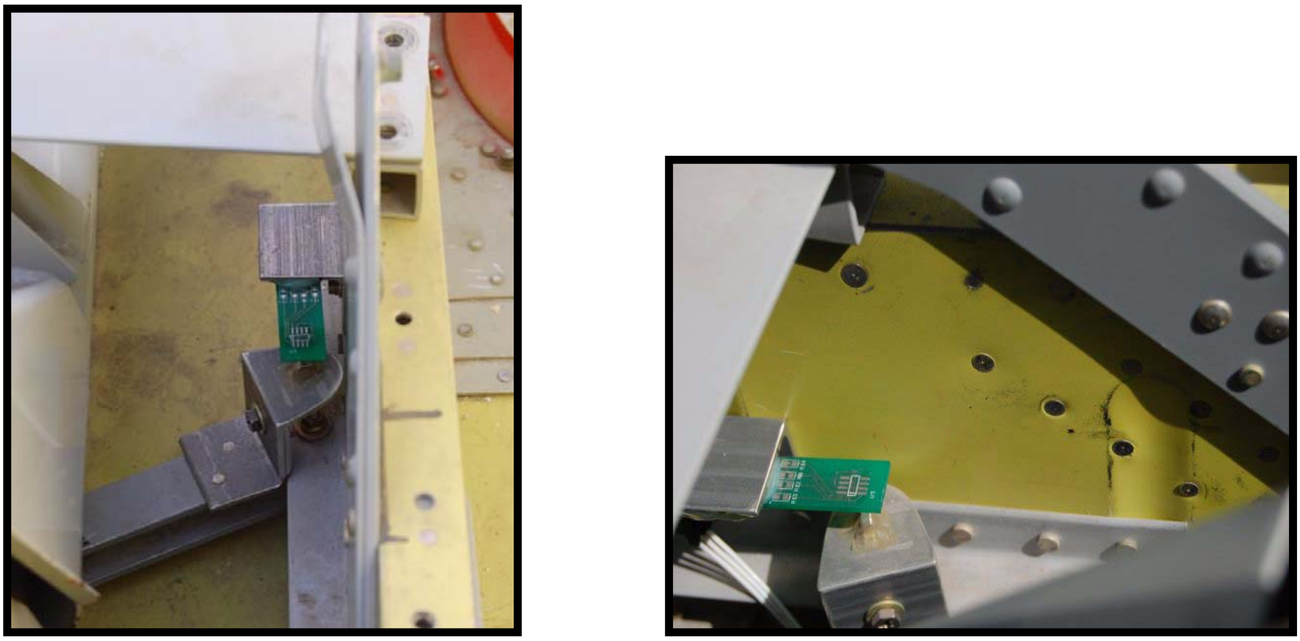


Figure 19: RV-8 Flap Sensor Installation

*Currently these sensor are only being used to determine flap location but the same technology will be installed on several control surfaces allowing their position to be made available on the CAN aerospace bus both locally for closed loop servos control and globally for third party flight control systems.

Fly-by-Wire for Experimental Aircraft - A Vision based on CANaerospace

During the Small Aircraft Transportation System (SATS) program conducted by NASA and the FAA in a partnership with the industry between 2001 and 2006, development of new technologies, logistics, systems and infrastructure were envisioned for general aviation in the following areas:

- High-volume operations at airports without control towers or terminal radar facilities
- Technologies enabling safe landings at more airports in almost all weather conditions
- Improved integration of general aviation aircraft into the air traffic control system, with complex flows and slower aircraft
- Improved single-pilot ability to function competently in evolving, complex airspace

Based on the technology design guidelines, system standards, and certification methods developed by the AGATE program, SATS encouraged the development of a new generation of personal transportation aircraft by industry from around the world. New materials, engines and Highway-in-the-Sky (HITS) technology emerged and resulted in unprecedented progress. The situational awareness provided by modern HITS Electronic Flight Instruments (EFIS) is truly amazing and has the potential to significantly improve the safety record for small aircraft operating under marginal weather conditions and over difficult terrain. Along with their success, the prices for these HITS EFIS dropped significantly, making the technology affordable even for very small and inexpensive aircraft.

The flight controls and electrical systems for light aircraft have not seen a comparable improvement, however. The advanced flight and electrical control system described hereafter shows how this gap may be closed by combining aircraft trim functions with a Command and Stability Augmentation System (CSAS), a three-axis autopilot and additional electrical system control functions using IMA components.

Today's light aircraft flight controls are conventional mechanical systems based on control rods and cables which are directly linked to the primary flight control surfaces (elevator, aileron and rudder). Many light aircraft also use flaps as secondary control surfaces and additional electric motors for flap actuation and trim functions. Automated flight control for light aircraft, however, is limited to the capabilites of "traditional" general aviation autopilots which use existing or supplementary trim motors. These autopilots provide attitude control around the pitch and roll axes combined with altitude, vertical speed and heading hold. Additionally, they allow flying horizontal and vertical tracks to navigational sources with reduced pilot intervention.

Especially in combination with HITS displays, the functions offered by current general aviation autopilots and trim systems reduce the pilot's workload considerably. On the other hand, the limited control bandwidth (run speed) of their control actuators and often missing flight state and air data signals do not allow the implementation of advanced flight control concepts. Table 7 contains some of the advanced concepts which are realized in the flight control systems of modern commercial airliners and many business and regional jets but have not found their way into light aircraft until today, mainly due to missing low cost technology.

Control Concept	Target
Automatic Turn Coordination	Stall/Spin Accident Prevention
Cruise Flight Side Slip Minimization	Performance Optimization, Fuel Saving
Automatic Configuration Change and Trim for Departure and Approach	Pilot's Workload Reduction, Flight Envelope Protection
Autopilot Control Bandwidth Improvement	Pilot's Workload Reduction
Gust Alleviation by Command and Stability Augmentation (CSAS)	Pilot's Workload Reduction, Passenger Comfort

Table 7: Advanced Flight Control Concepts

The affordable combined Air Data and Attitude and Heading Reference Systems (ADAHRS) necessary to realize these concepts have become available in part due to the fact that they are a vital part of HITS technology. In an effort to take this technology even further, the Rockwell Collins/Athena MicroINS [4] offers full Inertial Navigation System (INS) functionality for light aircraft at a very reasonable cost.

Furthermore, the use of CAN in large transport airplanes has skyrocketed with the Airbus A380 and the Boeing 787 programs, leading to more and more components like small and lightweight integrated servo systems are being developed and produced in substantial numbers. Taking advantage of these recent develoments and employing a CANaerospace-based IMA architecture, advanced flight controls for light aircraft has become viable.

Figure 20 shows a light airplane with its primary and secondary flight control surfaces. By adding Flettner servo tabs to aileron, elevator and rudder, the required degrees of freedom for the modern control methods as described in Table 7 can be realized.

The proposed flight control system architecture retains the mechanical controls but adds a system of integrated servo systems with differing authority and bandwidth enabling fly-by-wire style control without creating unresolvable safety issues. Integrated servo systems, available in linear and rotary versions provide a CAN interface and an internal servo controller which performs position control together with additional functions like force limiting and built-in test. A block diagram of such a “smart actuator” system is shown in Figure 21.

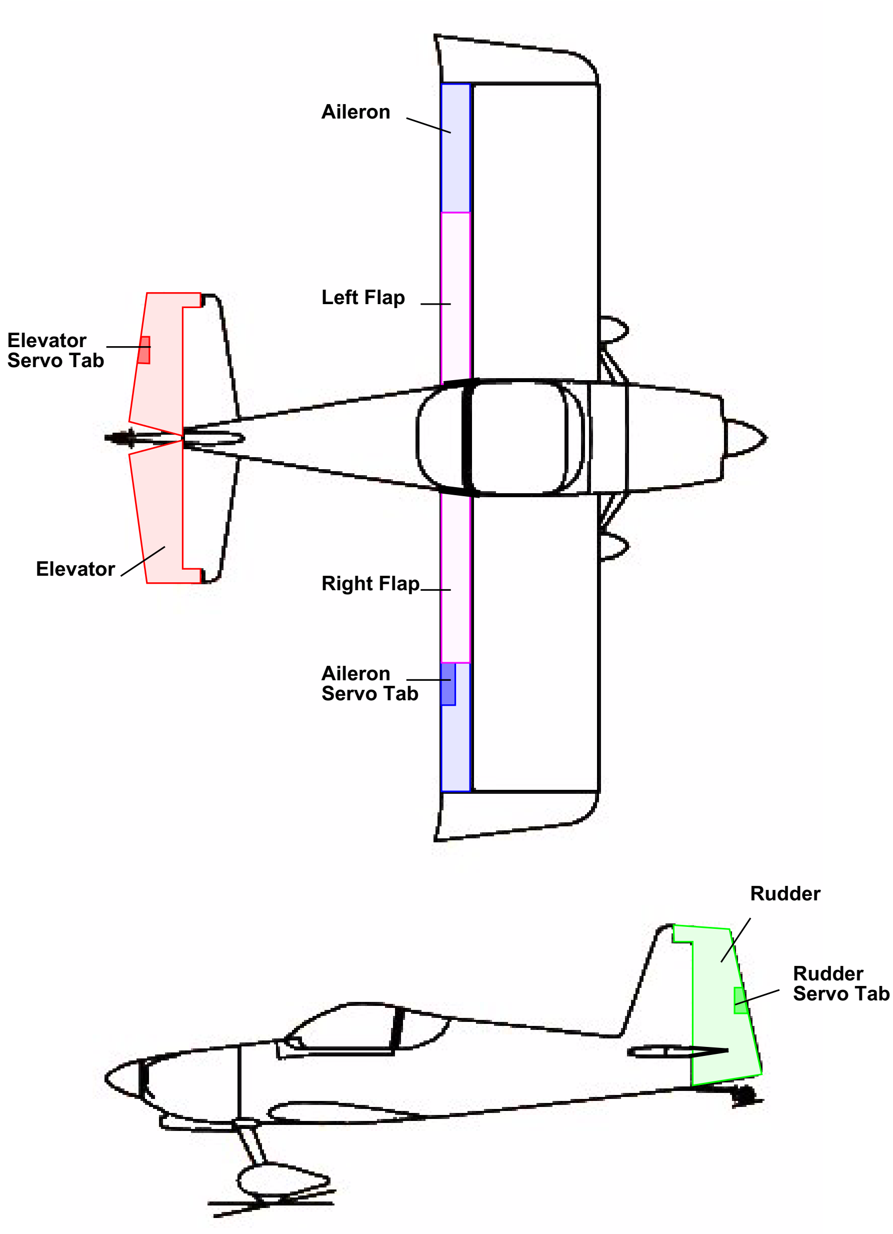


Figure 20: Light Aircraft with Control Surfaces supporting Advanced Flight Control Concepts

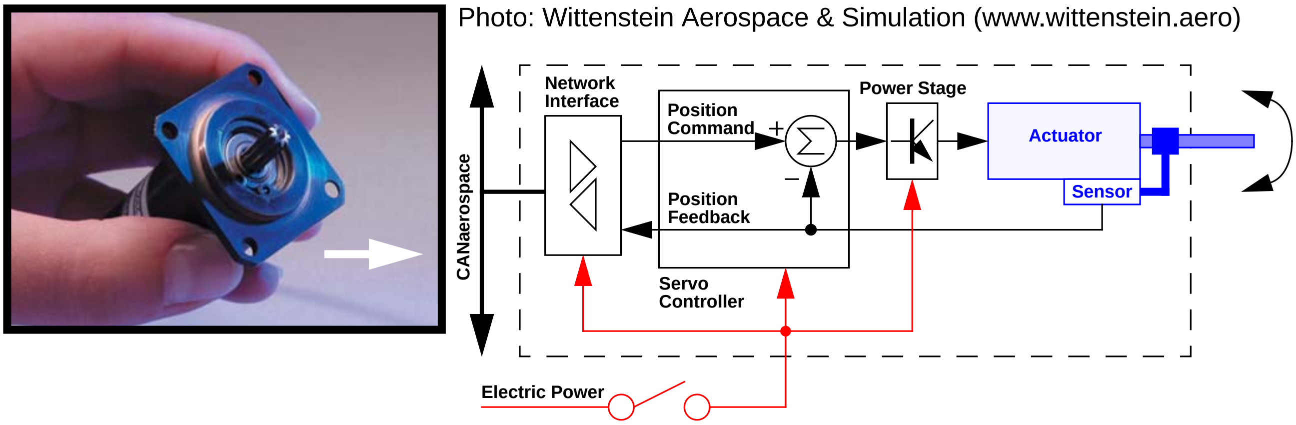


Photo: Wittenstein Aerospace & Simulation (www.wittenstein.aero)

Figure 21: Simplified Block Diagram of an Integrated Servo System ("Smart Actuator")

In order to enable modern control methods, the flight control actuators have to be integrated with the mechanical flight control system so that they provide adequate control authority and bandwidth. At the same time, however, the effect of system malfunctions on the controllability of the aircraft must be minimized. A solution to meet these conflicting targets is to split the control authority between two actuators. With the system architecture shown in Figure 22, the aircraft is always under control of the pilot even in case of actuator jam or actuator hard over, under the penalty of a higher pilot's workload. Additionally, a cutoff switch allows the pilot to deactivate the electric flight control system in case of failure by removing electrical power to the actuators.

In this system architecture, the stability augmentation actuator has high run speed but limited control authority and is used for the higher dynamic control functions like gust alleviation and command and stability augmentation. To accomplish this, the actuator can artificially change the length of the control rod to a certain degree (like +/- 15% of the full control authority) while the control link kinematics has to ensure that the high frequency actuator movement is irreversible and directed to the control surface only rather than backwards to the pilot controls (see Figure 23). For the rudder with its smaller bandwidth requirements, the stability augmentation actuator can be omitted.

The trim actuator has high control authority but limited run speed and drives a trailing edge Flettner servo tab. This tab moves in the opposite direction of the commanded deflection, creating an aerodynamic force that in turn moves the actual control surface. The advantage of this concept is that the small forces required to drive the servo tab allow a very lightweight actuator with little power consumption to be used.

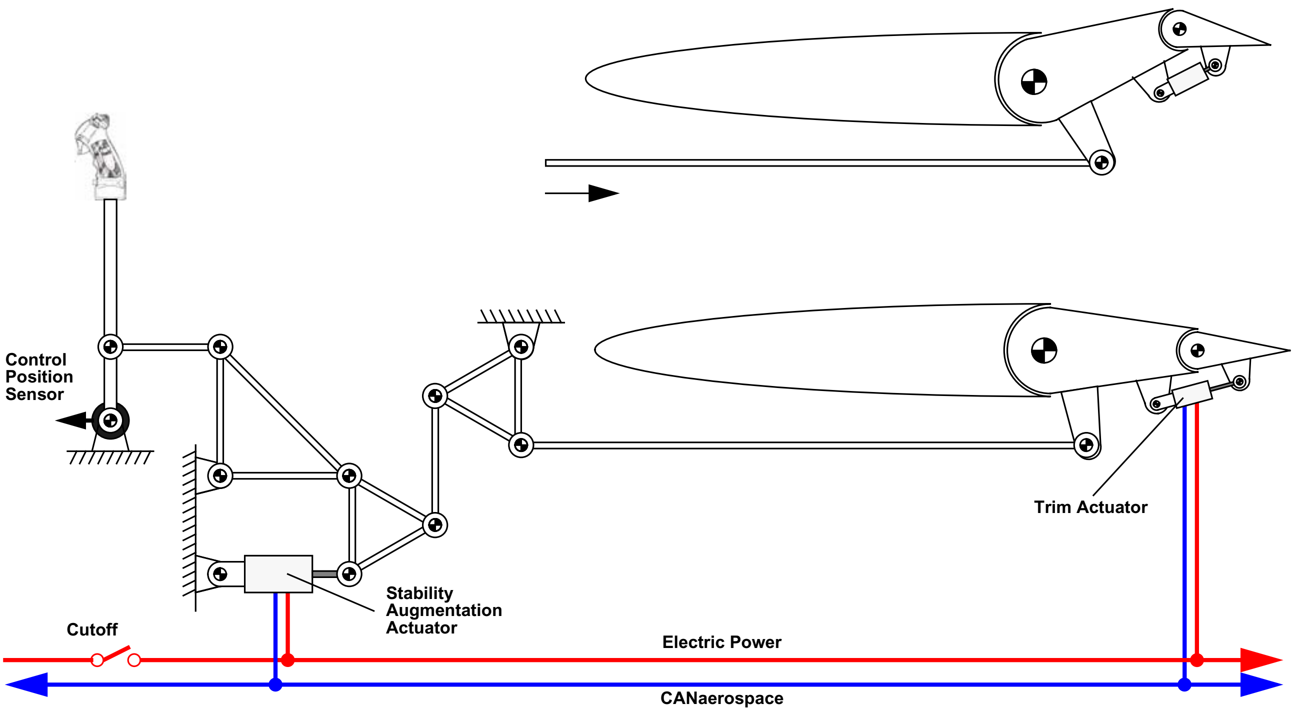


Figure 22: Integration of Smart Actuators with the Mechanical Flight Control System

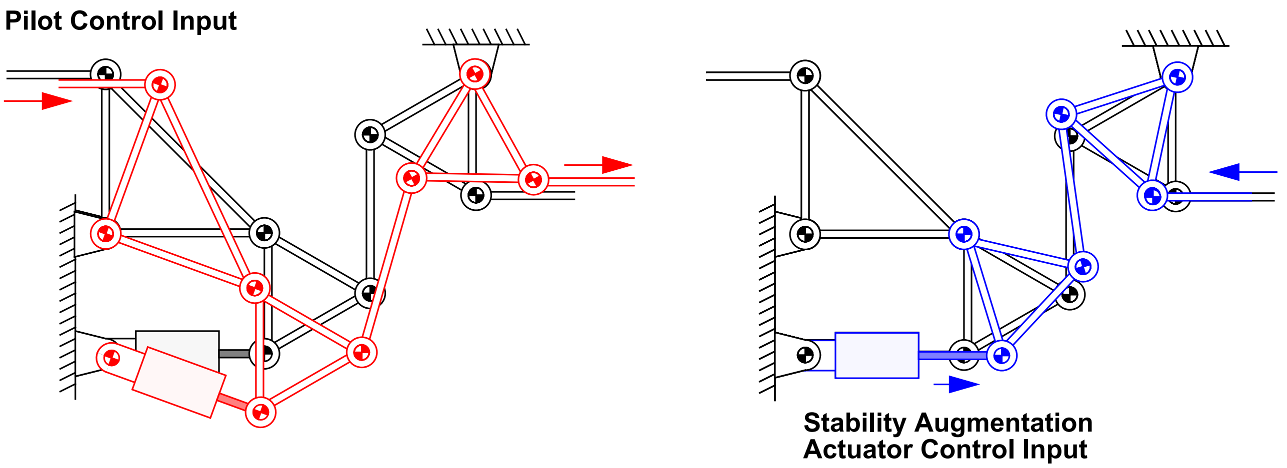


Figure 23: Adding Control Link Kinematics for Pilot and Actuator Control Inputs

Utilizing the approach described above, advanced flight control laws can make use of both actuators for each control surface by implementing control allocation. In general, control allocation directs high frequency positioning commands to the stability augmentation actuator, while the trim actuator is commanded to prevent the stability augmentation actuator from reaching its position limits. The trim actuator accomplishes this by using its control authority and moving into the same direction as the average total control command as shown in Figure 24.

The concept of dynamic control allocation [5] improves this method and provides an optimized, frequency dependent control distribution by automatic redistribution of the control effort when one of the actuators saturates in position or in rate. Dynamic control allocation allows advanced flight control laws to use the bandwidth and control authority offered by the combination of both actuators even more efficiently.

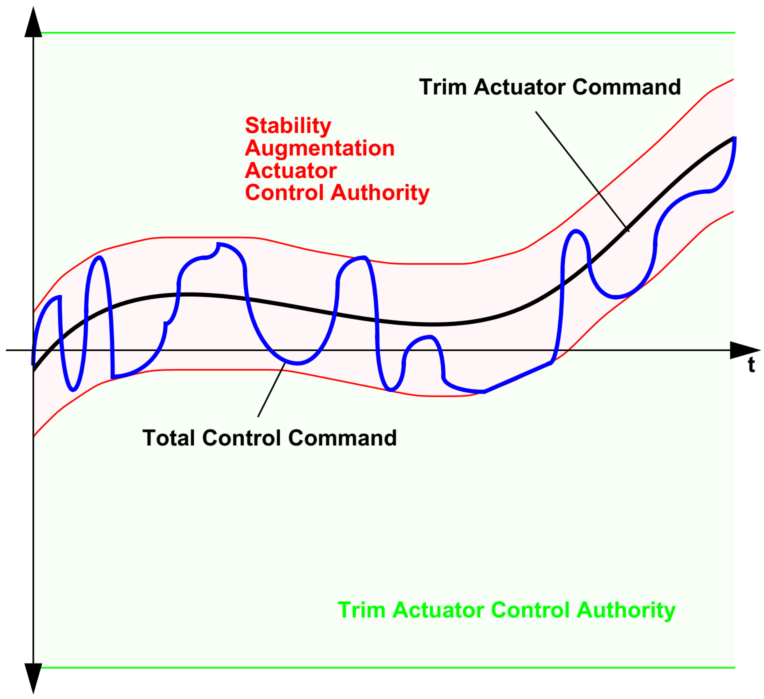


Figure 24: Control Allocation for Stability Control Actuator and Trim Actuator

Aside from providing advanced flight controls, an IMA system can also deploy numerous additional functions which reduce the pilot's workload when operating the airplane. Examples are automated control of electric consumers like aircraft lights and fuel pumps and the data exchange with Electronic Flight Instrumentation Systems (EFIS) to improve the pilot's interface with the various aircraft systems. Figure 25 shows such a flexible, CANaerospace-based IMA architecture which integrates several aircraft functions.

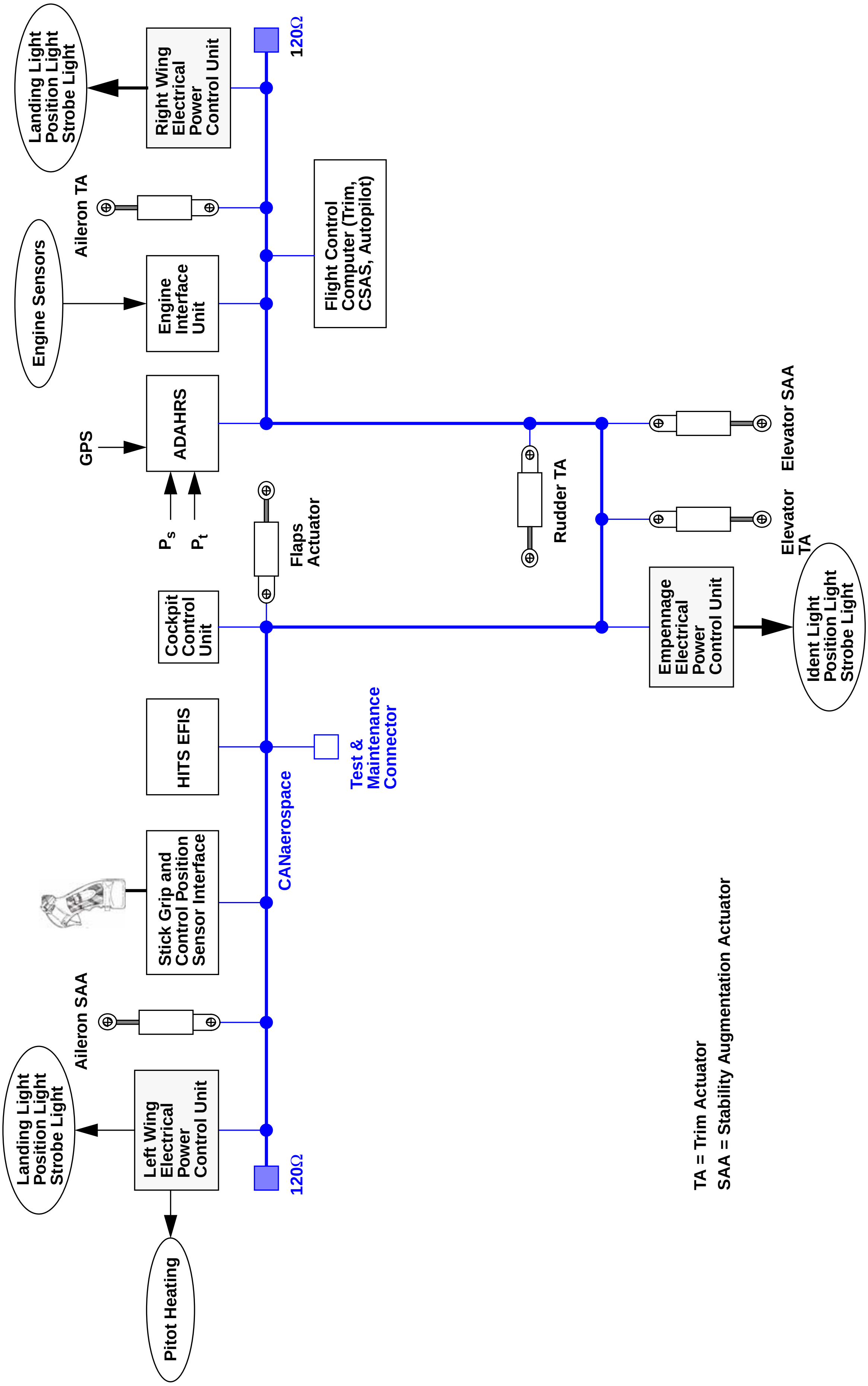


Figure 25: CANaerospace-based Fly-By-Wire IMA Architecture

This sample architecture allows the pilot to control the integrated aircraft functions individually through EFIS and cockpit control unit but also provides the capability to automize aircraft guidance and control. Considering the approach for landing, such a system has the ability to drive the flaps proportionally, continuously trim for the desired nose-up condition and airspeed and turn on landing lights and fuel pump without pilot intervention. At the same time it can exercise automatic turn coordination in order to prevent the pilot from accidentally skidding when turning towards final for landing.

Most certainly, not all light airplane owners want to install an IMA system with the complexity as described before. The modularity of IMA, however, makes it possible for each owner to tailor such a system according to his needs and still benefit from the simplicity, control augmentation and weight reduction that it offers. Taking advantage of the interoperability that is enforced by the IMA network, the owner may start with a minimum system and expand or upgrade this system step by step, like adding advanced flight control functions or flight management systems. Older avionic units which do not have the required interface may also be used if they are fitted with small IMA network converters. Finally, units with limited functionality can easily be replaced by newer, improved ones over time.

Conclusions and Outlook

Driven by the large aircraft manufacturers, Integrated Modular Avionics (IMA) systems based on reliable avionics networks represent the heart of all new commercial airliners. A fast growing number of business and commuter airplanes also makes use of this technology which enables advanced control concepts and offers significant weight and cost benefits at the same time. Unfortunately, the systems developed by the major avionics system suppliers for commercial aviation are too complex and too expensive for light airplanes.

In the meantime, however, the fast evolving computer and network technology has opened the door to IMA for light aircraft in an affordable way. The electronic products and networks developed for the automotive industry provide the necessary functions and can be adapted to aviation due to similar technical requirements and environmental specifications. Furthermore, a substantial cost reduction results from using automotive components which are produced in very large numbers and with guaranteed long term availability.

Based on this perception, this paper describes two IMA systems for light aircraft based on the leading automotive industry data bus (Controller Area Network, CAN). CAN is already used in millions of cars and trucks for embedded real time systems communication. Modern commercial airliners also utilize CAN extensively for numerous systems of all criticality levels. The combination of CAN and the CANaerospace interface standard provides a network that fulfills all requirements for mission and safety critical applications in aviation and allows us to apply CAN not only to secondary aircraft systems, but also to primary functions like flight controls.

The RV-7ca project demonstrates that a CANaerospace-based IMA system can successfully be implemented for a light airplane at reasonable cost and effort. The benefits of this technology for homebuilders are obvious and verifiable. By using existing technology from the transportation industry a substantial reduction in parts count and cost can be realized for intelligent controller design over systems developed just a few years ago. Using the current generation of smart power switches and micro controllers, electrical loads and servos can be controlled and monitored with better precision and reliability. By replacing mechanical sensors with sealed non-contact sensors, both the long term stability and reliability of servos can be improved. Using a communications bus and distributed power modules reduces wiring cost and control panel complexity. Using aviation standards such as CANaerospace creates an open system that can be more easily monitored, repaired, or augmented than proprietary systems linked to a single manufacture.

The light airplane Fly-By-Wire IMA architecture developed in this paper employs CANaerospace and takes advantage of new developments in electric drive technology to create a state-of-the-art flight control system. This system introduces advanced flight control concepts for small airplanes which are presently available for larger aircraft only. These modern control methods reduce the pilot’s workload considerably and have the potential to significantly improve the safety record for small airplanes operating under marginal weather conditions.

The described light airplane IMA architectures provide an outstanding level of modularity and flexibility due to the open CANaerospace interface standard. Unlike proprietary networks used for other IMA architectures, CANaerospace does not require specific components, tools or hardware. All that is needed to implement CAN aerospace are affordable off-the-shelf products available from numerous vendors. Furthermore, the use of the standard itself is free; Absolutely no cost or royalties apply.
EFIS manufactures can use the CANaerospace to leverage third party sensors and actuators into their own system using standard CANaerospace identifiers. An alliance between kit plane manufacturers, homebuilders and avionics suppliers would have the potential to initiate the design of new or the upgrade of existing avionics

components with CANaerospace interface, creating the basis for a substantial number of IMA systems in light aircraft. Such an alliance could generate the momentum to make the vision of light airplane IMA and fly-by-wire become reality within a very short period of time.

References

[1] Robert Bosch GmbH: CAN Specification 2.0
http://www.semiconductors.bosch.de/pdf/can2spec.pdf

[2] Stock Flight Systems: CANaerospace Specification V 1.7
http://www.stockflightsystems.com

[3] NASA Langley Research Center: System Standard for the AGATE Airplane Avionics Data Bus, AGATE-WP01-001-DBSTD

[4] Rockwell Collins, Inc. Control Technologies: MicroINS data sheet
http://www.rockwellcollins.com/athena/products/commercial/microins/Micro-INS-ds.pdf

[5] Ola Härkegaard: Dynamic Control Allocation Using Constrained Quadratic Programming
Linköping University, 581 83 Linköping, Sweden
http://research.harkegard.se

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Mark Swaney

Technische Universität München, Institute of Flight System Dynamics

Acronym List

ADAHRS	Air Data and Attitude and Heading Reference Systems
AGATE	Advanced General Aviation Transport Experiments
ARINC	Aeronautical Radio, Inc. (www.arinc.com)
ATM	Anyone-To-Many (communication)
CAN	Controller Area Network
CPU	Central Processing Unit
CSAS	Command and Stability Augmentation System
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DITS	Digital Information Transfer Standard
DSD	Debug Service Data
EED	Emergency Event Data
EFIS	Electronic Flight Instrument System
EMI	Electromagnetic Immunity
FAA	Federal Aviation Administration (www.faa.gov)
FWF	Fire Wall Forward
GPS	Global Positioning System
HIRF	High Intensity Radiated Fields
HITS	Highway-In-The-Sky
IMA	Integrated Modular Avionics
INS	Inertial Navigation System
LCC	Logical Communication Channel
LLC	Logical Link Control
LRU	Line Replaceable Unit
MAC	Media Access Control
NASA	National Aeronautics and Space Administration (www.nasa.gov)
NOD	Normal Operation Data
NSH	Node Service data - High priority
NSL	Node Service data - Low priority
PTP	Peer-to-Peer (communication)
SAA	Stability Augmentation Actuator
SATS	Small Aircraft Transportation System
SSG	Serial Stick Grip
TA	Trim Actuator
TCP/IP	Transmission Control Protocol/Internet Protocol
UDH	User-Defined Data - HighPriority
UDL	User-Defined Data - Low Priority
UDP/IP	User Datagram Protocol/Internet Protocol

